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original research

Altered Vertical Ground Reaction Forces in Participants With Chronic Ankle Instability While Running

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Context: Altered gait kinetics may increase the risk of long-term injuries in participants with chronic ankle instability (CAI). Vertical ground reaction forces (vGRFs) can provide insight into how body loading is altered.

Objective: To compare the components of vGRFs while running in participants with or without CAI.

Design: Cohort study.

Setting: University biomechanics laboratory.

Patients or Other Participants: Twenty-four experienced, college-aged runners. Groups were categorized by the presence (CAI group) or absence (control group) of CAI through self-reported questionnaires.

Intervention(s): After a warm-up period, all participants ran on an instrumented treadmill for 5 minutes at 3.3 m/s. Data were collected during the last 30 seconds. Five continuous trials of heel-to-toe running were identified per participant and averaged for statistical analysis.

Main Outcome Measure(s): The dependent variables were impact peak force (N/body weight [BW]), active peak force (N/BW), time to impact peak force (milliseconds), time to active peak force (milliseconds), and average loading rate ([N/BW]/s).

Results: A difference was found between groups ($P = .002$). The CAI group had higher impact peak forces ($P = .001$) and active peak forces ($P = .002$) compared with the control group. The CAI group also had an increased loading rate ($P = .001$) and a shorter time to reach the active peak force ($P = .001$) compared with the control group. No difference was seen between groups in the time to reach the impact peak force ($P = .952$).

Conclusions: Participants with CAI produced altered vGRFs and loading rates while running. Altered loading rates could predispose individuals with CAI to stress-related injuries and repetitive sprains.

Key Words: biomechanics, gait, kinetics, stress fractures

Key Points

- The group with chronic ankle instability demonstrated greater vertical ground reaction forces and initial and active peak forces.
- Those with chronic ankle instability also had increased loading rates, which could make them vulnerable to stress injuries and sprains.

In a recent sampling of collegiate and high school athletes, the prevalence of chronic ankle instability (CAI) was 23.4%.[1] Chronic ankle instability is a complex injury caused by mechanical and functional insufficiencies, found after the resolution of an initial lateral ankle sprain, which can lead to repetitive sprains and instability of the ankle joint.[2] Typically, individuals with CAI report feelings of the ankle "giving way" during activity.[3]

Recently, researchers[4] studied the effect of CAI on an individual's gait pattern. Through various portions of the gait cycle, people with CAI walk and run with altered ankle and foot kinematics compared with uninjured people.[4] In walking, kinetic differences include greater peak plantar pressure in the midfoot and lateral forefoot,[5] a laterally deviated center of pressure (COP),[6] and increased braking and propulsive forces[7] compared with uninjured participants. While running, individuals with CAI have increased pressure within the lateral rear foot and a lateral COP trajectory compared with a medial COP trajectory in healthy individuals during the loading response phase.[8] These alterations may place the ankle joint in a position that is more susceptible to repetitive ankle sprains.[9] However, in this population, little is known regarding vertical ground reaction forces (vGRFs), a common measurement of forces and loading rates of the lower extremity.

In a vGRF graph of rearfoot strikers, 2 peaks are produced while running.[10] The initial impact peak occurs during the first 50 milliseconds as the foot comes into contact with the ground.[10] Next, a second peak, known as the active peak, occurs during the propulsion phase of running gait.[11] The *active peak* is the force generated by the leg as the plantar-flexor muscles contract to advance the leg forward during the middle of the stance phase.[12] From the impact peak, the loading rate can be calculated. The loading rate is the average rise in force production occurring from

20% to 80% of the time between initial contact and the impact peak force.[11] Previous authors associated increased loading rates in participants with a history of tibial and metatarsal stress fractures,[13] and alterations in vGRF values have been seen in patients with asymmetric ankle osteoarthritis (OA).[14]

To date, only 1 group has examined vGRFs in a CAI population while running and walking.[15] Brown et al[15] investigated the active peak vGRF and time to peak vGRF while running. For the peak vGRF, they found no differences between 2 subgroups of CAI (mechanical ankle instability and functional ankle instability) compared with participants who had an initial ankle sprain but no residual symptoms.[15] However, no uninjured control group was tested. Because of evidence for vGRF alterations in individuals with CAI and other populations during other dynamic movements, it is necessary to determine if participants with CAI have altered vGRF compared with uninjured control participants while running.

Therefore, the purpose of our investigation was to explore if differences in vGRFs existed in individuals with CAI compared with controls. We hypothesized that individuals with CAI would generate higher vGRFs and loading rates than healthy individuals.

METHODS

Participants

Twenty-four participants (12 men, 12 women; age = 20.78 ± 2.70 years, height = 1.75 ± 0.09 m, mass = 67.28 ± 10.56 kg) volunteered for this study. Participants completed 3 questionnaires: the Physical Activity Readiness Questionnaire, a health and running history questionnaire, and the Identification of Functional Ankle Instability (IdFAI) Questionnaire. The Physical Activity Readiness Questionnaire screened individuals for predisposing risk factors that might affect their safe participation in the physical activity associated with the study.[16] We chose this health and running history questionnaire because it encompassed all of the inclusion and exclusion factors for participation in the study. The IdFAI was used to identify individuals with CAI.[17]

Participants were assigned to the control or CAI group based on their self-reported injury history and IdFAI score. Inclusion criteria for the CAI group were (1) a history of at least 1 self-reported lateral ankle sprain that occurred at least 12 months before study enrollment, (2) a history of recurrent sprains or feelings of giving way during functional activity, and (3) a score of 11 or higher on the IdFAI.[18] If the participant had bilateral CAI, the ankle with the higher self-reported IdFAI score was the test limb. These inclusion criteria were based on the International Ankle Consortium's definition of CAI.[18] For the control group, participants had no self-reported history of injury to either ankle joint on the health history questionnaire. Ankles of control participants were matched with a CAI counterpart. Exclusion criteria for both groups were (1) a history of surgery or fractures in the lower extremity, (2) an acute lower extremity injury within the past 3 months, (3) enrollment in any formal lower extremity rehabilitation program, (4) the use of orthotics while running, and (5) the presence of a midfoot or forefoot striking pattern during running. Finally, because of the instrumentation used in the study, all participants needed to be *active runners*, defined as having at least 1 year of consistent running experience and currently running a minimum of 20 miles (32 km) per week (MPW).[11]

As a result, 13 healthy individuals were in the control group (7 men, 6 women; age = 20.4 ± 3.6 years, height = 1.75 ± 0.08 m, mass = 66.49 ± 10.38 kg, MPW = 37.75 ± 22.51, IdFAI score = 0.08 ± 0.23) and 11 individuals were in the CAI group (5 men, 6 women; age = 21.2 ± 1.3 years, height = 1.73 ± 0.09 m, mass = 68.07 ± 11.16 kg, MPW = 46.02 ± 19.58, IdFAI score = 16.00 ± 6.63). All participants signed an informed consent form that was approved by the Indiana University and the University of Evansville Institutional Review Boards for the Protection of Human Subjects, which also approved the study.

Procedures

All vGRF data were collected using an instrumented treadmill (model Fully Instrumented Treadmill; Bertec Corp, Columbus, OH) with a sampling rate of 1200 Hz. Foot strike, marking the beginning of the stance phase, was identified when the force plate registered a vGRF greater than 30 N.[11] Toe-off, marking the termination of the stance phase, was identified when the force plate registered a vGRF of less than 30 N.[11]

Participants warmed up on the treadmill for 5 minutes at a self-selected pace. To mimic the most natural running conditions, all participants ran in their standard running shoes. All shoes were visually inspected before testing and determined to be either neutral-cushioned or mild stability shoes. Each individual was given an opportunity to complete his or her prerun stretching routine between the warm-up and test trial. For the test trial, participants ran at a standardized speed of 3.3 m/s for 5 minutes. The pace was selected based on previous running-related literature[15] for this population. Also, this pace was similar to each person's easy running pace, which was verbally confirmed with each participant during the warm-up period. Data were captured during the last 30 seconds of the trial. The individual was then given an opportunity for a 5-minute cool-down period.

Data collected using the instrumented treadmill were interfaced with Vicon Nexus (version 1.7; Vicon, Centennial, CO). Group allocation was removed before processing to limit researcher bias. A fourth-order, low-pass Butterworth filter with a cutoff of 45 Hz was applied to all vGRF data.[19] All vGRF values were normalized to each participant's body weight (BW).[20] Five consecutive stance phases of the test limb were used for analysis.[11] A custom program in R software (R Development Core Team, Vienna, Austria) was used to identify each dependent variable.

The dependent variables were impact peak force, time to impact peak force, active peak force, time to active peak force, and average loading rate. The *impact peak force* was defined as the maximum in the vGRF data within the first 50 milliseconds of the stance phase, normalized to BW (N/BW).[10] This peak is absent in midfoot and forefoot strikers.[11] The absence of an impact peak on analysis would exclude the participant from the study because of the striking pattern. The *active peak force* was defined as the greatest amount of force produced by the participant during

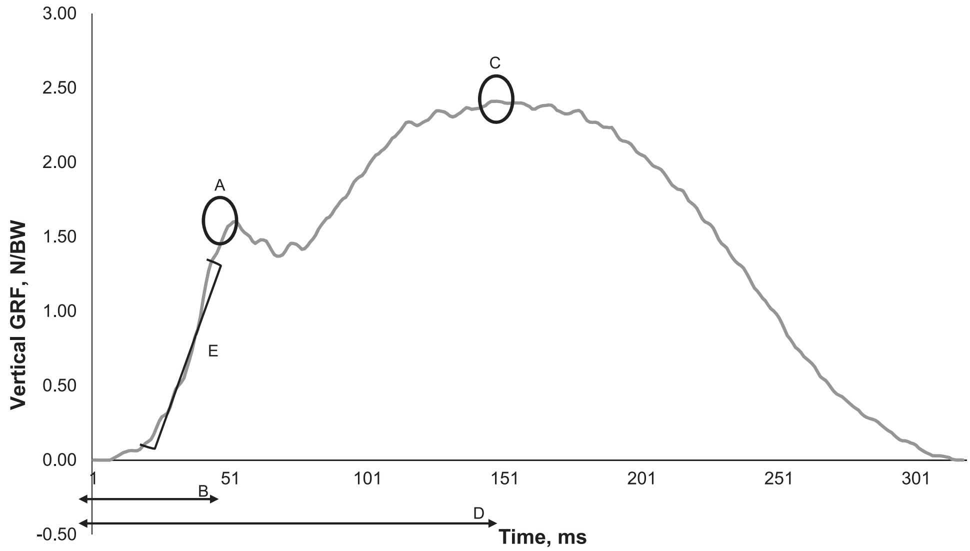

Figure 1. Dependent variables of the vertical ground reaction force (GRF) curve. A, Impact peak (N/BW). B, Time to impact peak (milliseconds). C, Active peak (N/BW). D, Time to active peak (milliseconds). E, Average loading rate ([N/BW]/s). Abbreviation: BW, body weight.

a gait cycle, normalized to BW (N/BW).[11] *Time to impact peak force* was the time from initial contact to the impact peak force expressed in milliseconds.[11] *Time to active peak force* was the time from initial contact to the active peak force expressed in milliseconds.[11] The *average loading rate* was defined as the slope of the impact peak from 20% to 80%, expressed in BW divided by seconds ([N/BW]/s).[11] Dependent variables depicted on a vGRF graph are shown in Figure 1. We conducted a 1-way analysis of variance in SPSS (version 20; IBM Corp, Armonk, NY) to perform pairwise comparisons of the dependent variables between groups. The significance level was set at $P \leq .05$. Because of the small sample size, the Hedges *g* was used to report effect sizes.

RESULTS

Group means, standard deviations, effect sizes, and 95% confidence intervals for the effect size of each dependent variable are shown in the Table. Representative vGRF graphs from each group are presented in Figure 2. Impact peak forces were greater in participants with CAI than in controls ($P = .001$). Those with CAI had an increased average loading rate compared with control participants ($P = .001$). Also, the active peak force was higher in those with CAI than in controls ($P = .002$). The CAI group reached the active peak force in a shorter time than did the control group ($P = .001$). No difference was found between groups in the time to reach impact peak force ($P = .952$).

DISCUSSION

The principal finding of our study was that individuals with CAI presented with altered kinetic variables compared with control participants while running. As hypothesized, individuals with CAI presented with increased peak forces and loading rates and a shorter time to active peak force than the control group. To our knowledge, we are the first to report vGRFs while running in individuals with CAI compared with a control group. Our study was exploratory in nature, to determine if differences exist in CAI individuals during a common athletic activity. All of the significant dependent variables had very large effect sizes when we used the Hedges *g* to correct for a small sample size. The lower limit of the 95% confidence interval of each effect size ranged from moderate to very large for each of the significant dependent variables. Because we used the recommended inclusion criteria of the International Ankle Consortium to identify those with CAI and found several large effect sizes, the data appear to show the true kinetic behaviors of these individuals during a common athletic activity. Given that vGRF increases as a person increases speed, running may naturally exacerbate the differences seen between groups compared with a condition that naturally produces smaller vGRF, such as walking.

Previous researchers have proposed that individuals with CAI land with a stiffer strategy as a compensatory mechanism to protect the ankle joint from repetitive sprains. De Ridder et al[9] found that during a stop-jump

Table. Peak Ground Reaction Forces, Time to Peak Ground Reaction Forces, and Loading Rates Between Groups

	Group, Mean ± SD			
Variable	Control	Chronic Ankle Instability	Hedges *g*	Effect-Size Confidence Interval
Impact peak, N/BW	1.69 ± 0.20	2.05 ± 0.24	1.59	0.67, 2.51
Time to impact peak, ms	38.11 ± 2.07	38.07 ± 1.49	−0.02	−0.82, 0.78
Active peak, N/BW	2.52 ± 0.08	2.71 ± 0.18	1.36	0.47, 2.25
Time to active peak, ms	131.46 ± 6.09	117.27 ± 5.96	−2.27	−3.30, −1.24
Average loading rate, (N/BW)/s	77.77 ± 10.04	93.84 ± 10.89	1.49	0.58, 2.39

Abbreviations: BW, body weight.

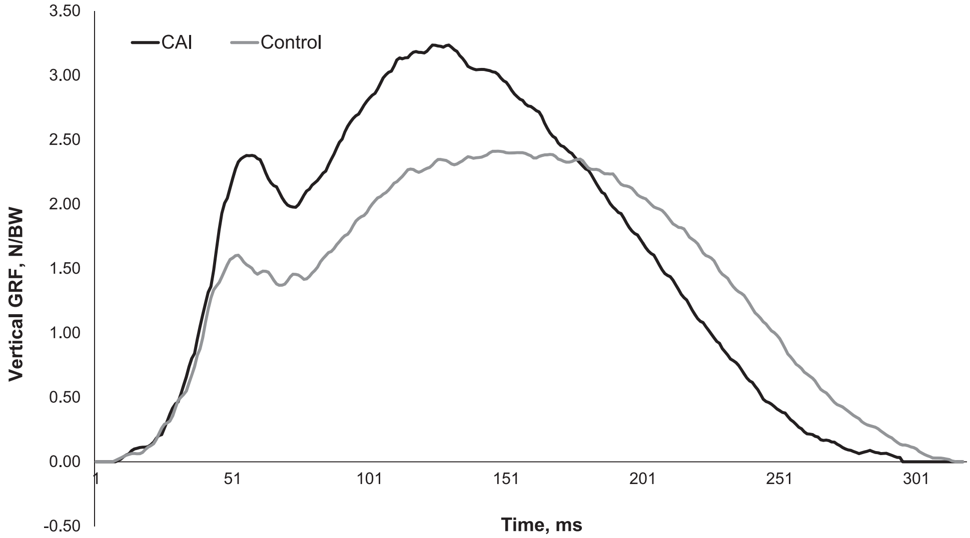

Figure 2. Comparison of 2 vertical ground reaction force (GRF) curves between groups. Abbreviations: BW, body weight; CAI, chronic ankle instability.

task, people with CAI landed with less plantar flexion at touchdown. During gait, the impact peak force is reached during the first 10% of the stance phase, and its magnitude largely depends on the impact speed of the initial loading of the weight onto the limb.[21] As the foot makes contact with the ground, the GRF is transferred up the kinetic chain via the joints from the fat pad through the calcaneus and talus into the ankle joint and then through the lower leg, dissipating the GRF.[22] If the available range of motion is decreased due to the body's attempt to protect the ankle joint, this could potentially lead to an increase in the peak forces, as seen in our study. A stiffer landing pattern would be represented by the increase in peak forces seen in the CAI group. However, we cannot directly relate the cause of the altered vGRF variables noted in the CAI group to any functional deficits seen in participants with CAI because we did not collect kinematic or electromyographic data. Future researchers should focus on determining which functional deficits in CAI are correlated with the altered vGRF variables.

Although individuals with CAI may attempt to protect the injured ankle during activity, strength differences may also contribute to the increase in peak forces. In isokinetic muscle testing, those with CAI had a 24% decrease in eccentric tibialis anterior strength compared with control participants.[23] Theoretically, if the tibialis anterior muscle is unable to control the descent of the foot during initial contact, then the foot will strike with greater magnitude, causing an increased impact peak. A decrease in strength of the tibialis anterior may contribute to the increased impact peaks seen in individuals with CAI.

After the impact peak occurs, the COP continues to move forward, shifting the BW over the stance limb. At midstance, the subtalar joint begins to supinate as the body accelerates, marking the active peak on a vGRF graph.[21] Huang et al[24] reported that individuals with CAI had increased pressure under the first and third metatarsal heads during this period. This increased pressure was similar to our findings and may contribute to the peroneus longus's attempt to stabilize the ankle joint as the subtalar joint supinates to prevent additional ankle sprains as the joint unloads. Hopkins et al[6] found an increase in peroneus longus muscle activity at toe-off in those with CAI compared with control participants. After landing, the CAI group had decreased ankle-joint stiffness during sporting maneuvers compared with controls.[25] The active peak force could represent the contractions of the lower limb muscles as they attempt to stabilize the ankle joint during the mid to late stance phases. More research is needed to correlate activation patterns of the lower extremity musculature in participants with CAI and their kinetic patterns.

It is also interesting to note that the CAI group produced active peak force in a shorter time than the control group. No other authors have shown a difference in time-to-peak-force values while running. It is possible that participants with CAI could rely more on the unaffected side during gait, causing a shorter stride on the affected side. However, we did not compare vGRF data between limbs within participants.

Clinically, an increase in loading rates places the structures of the ankle joint under more stress.[13] In a meta-analysis,[13] increased loading rates in vGRFs were correlated with lower extremity injuries, such as tibial and metatarsal stress fractures. Runners with a history of overuse injuries had increased impact peaks and loading rates.[21] Therefore, the increased loading rates in individuals with CAI could place them at an increased risk for developing a lower extremity stress-related injury in that limb.

Moreover, the increased loading rates and peak forces could place abnormal stress on the ankle joint, causing individuals with CAI to be more susceptible to developing OA. Previous investigators[26] observed that 66% of patients with CAI had lesions present within the cartilage. Arthroscopic findings[26] have confirmed lateral, rotational, and medial instability of the talus, depending on the severity of the CAI. If the talus becomes unstable as the amount of force increases within the ankle joint, the shearing and rotational forces acting on the cartilage will increase, which could lead to degeneration of the cartilage. Furthermore, a link has also been found between varus malalignment of the ankle joint and CAI.[26] Malalignment of the ankle joint increases stress on the superficial articular cartilage, a key structure in preventing OA.[27] On average, each limb of a runner strikes the ground approximately 300 times per kilometer[28]; therefore, even a small increase in peak forces could cause the affected structures to degenerate. Future authors should examine if increased vGRFs are related to the development of OA or predispose individuals to an increased risk of stress fractures.

Finally, the altered kinetic variables and positioning of the lower extremity known from previous work may provide insight as to why individuals with CAI continue to sustain repeated ankle sprains. In examining the risk factors associated with anterior cruciate ligament injuries, Hewett et al[29] identified a 20% increase in peak vGRF and a 16% decrease in stance time. From this body of work, a clinical goal in ACL injury prevention of decreasing impact forces during landing was developed. This literature may provide insight into how we can prevent ankle sprains in individuals with CAI. Already, gait retraining has become an effective tool in decreasing loading rates in participants with previous stress fractures.[10] In addition, short-term rehabilitation programs improved function and gait in individuals with CAI.[30] Given the connection between decreasing loading rates and peak forces in reducing the risk of other lower extremity injuries, returning to their normative mechanics should be considered a rehabilitative goal for those with CAI. Future researchers should consider which rehabilitative techniques would provide the best outcomes for decreasing peak forces and loading rates in these individuals.

Some limitations of the study need to be noted in regard to the internal and external validity. Our design was a retrospective cross-sectional analysis; therefore, a direct cause-and-effect relationship between the kinetic differences and movements of the ankle joint cannot be established. However, the vGRF data provide a basis for future investigators to explore the kinetic changes at the ankle joint in participants with CAI. Next, all participants ran in their usual running shoes during testing. Typically, a common approach in the literature is to have participants run in a standardized running shoe or barefoot; however, this may not accurately represent their natural movement patterns. Upon each participant's arrival at the laboratory, we visually inspected his or her shoes. All participants ran in either neutral cushioned or mild stability shoes. Although shoe type (minimalist versus standard cushioning) can alter vGRF,[19] differences in midsole thickness do not alter vGRFs while running.[31] Given the large effect size and the similarity of shoes in each group, we do not believe the difference in shoe types influenced our results, and it allowed for a more realistic kinetic profile of vGRFs in a CAI group. A third limitation may be the standardized running speed, which may not have been a direct representation of each participant's preferred running speed. We chose a standardized speed that would represent each participant's natural running ability. Although the average MPW reported by each participant varied, there was no difference between groups ($P = .337$). Also, each participant ran more than the minimum average mileage required per week. The physical activity baseline and running speed used in this study have been used previously in other running studies.[30] Finally, not matching limb dominance between groups and the reporting of vGRF in only 1 limb may have left out information that could be used to further investigate the differences between groups.

CONCLUSIONS

In this exploratory study, we found kinetic differences between participants with CAI and control participants while running. We are the first to report differences in vGRFs in individuals with CAI while running. Increased loading rates, impact peaks, and active force peaks may contribute to an altered landing pattern used by individuals with CAI to protect the ankle joint. Additionally, increased loading rates and vGRFs could predispose participants with CAI to an increased risk of stress-related injuries and repetitive ankle sprains.

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